

Drawbacks of the Criteria Used to Identify Isolated Galaxies

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ABSTRACT. Using the volume-limited main galaxy sample of the Sloan Digital Sky Survey Data Release 6 (SDSS DR6), we explore drawbacks of the selection criteria of isolated galaxies developed by Karachentseva, published in 1973. We find that about 35.36% of the isolated galaxies identified by Karachentseva’s main criterion $x_{i,j} \geq 20 \times a_j$ lie in groups or clusters, which may lead to the result that there are no significant statistical differences of galaxy properties between group and cluster galaxies and isolated galaxies. Our work at least suggests that searches for better methods to find isolated galaxies are needed.

1. INTRODUCTION

Isolated galaxies, which may have experienced no major interactions in billions of years and had very probably evolved without any external perturbation, are a group of special and rare galaxies in the universe. They often reside in the most underdense regions, and can be served as an interesting sample for studies of the effects of underdense environment on galaxy properties (Adams et al. 1980; Haynes & Giovanelli 1980; Koopmann & Kenney 1998; Rojas et al. 2004; Hoyle et al. 2005; Rojas et al. 2005; Deng et al. 2006a, 2007a, 2007b). For example, Deng et al. (2007b) showed that isolated galaxies have a higher proportion of faint galaxies and a lower proportion of luminous galaxies than member galaxies of groups. In recent years, many authors performed various studies involving isolated galaxies (Colbert et al. 2001; Pisano & Wilcots 2003; Sauty et al. 2003; Marcum et al. 2004; Reda et al. 2004; Stocke et al. 2004; Varela et al. 2004; Allam et al. 2005; Conroy et al. 2005; Verdes-Montenegro et al. 2005; Hau et al. 2006; Karachentsev et al. 2006; Reda et al. 2007).

The first systematic compilation of isolated galaxies was made by Karachentseva (1973). According to Karachentseva’s (1973) selection algorithm, a galaxy i with angular diameter a_i is considered isolated if the projected sky separation $x_{i,j}$ between this galaxy and any neighboring galaxy j with angular diameter a_j satisfies the following two criteria: $x_{i,j} \geq 20 \times a_j$; $\frac{1}{4}a_j \leq a_i \leq 4 \times a_j$. To date, the Catalog of Isolated Galaxies constructed by Karachentseva (1973) (hereafter referred to as CIG, Karachentseva 1973; 1050 galaxies) still is a popular sample. Stocke et al. (2004) used this sample to investigate a candidate list of >100 very isolated early-type galaxies. Karachentsev et al. (2006) searched for “strange” cases of interaction where the second interacting companion is invisible. The AMIGA project (Analysis of the interstellar Medium of Isolated Galaxies, see <http://www.iaa.es/AMIGA.html>) compiled a multiwavelength database of isolated

galaxies, and presented a complete refinement of properties for galaxies in this catalog (Verdes-Montenegro et al. 2005; Sulentic et al. 2006; Lisenfeld et al. 2007; Verley et al. 2007a; Verley et al. 2007b). Using this catalog as a starting point, Verley et al. (2007a) generated a catalog of approximately 54,000 potential neighbors. In order to estimate the influence exerted by the neighbor galaxies on the isolated galaxy, Verley et al. (2007b) computed two parameters: the local number density of neighbor galaxies, and the tidal strength affecting the isolated galaxy, and showed that both parameters together provide a comprehensive picture of the environment.

Karachentseva (1973) did not use redshifts to produce CIG, since at that time few such data existed. Isolated galaxies were identified only on the observed angular sizes and distances between galaxies. Thus, this sample is representative, but not fully complete, because a truly isolated galaxy may be excluded from CIG due to a projected background/foreground neighbor: galaxies isolated in space do not necessarily appear isolated in the sky. In addition, CIG only is a sample of galaxies isolated from similarly sized neighbors.

Nowadays we can use databases with redshifts and determine whether a galaxy is the most isolated in the three-dimensional space. Colbert et al. (2001) constructed a well-defined sample of 30 isolated galaxies with no other cataloged galaxy with known redshift lying within a projected radius of $1 h_{100}^{-1}$ Mpc and $\pm 1000 \text{ km s}^{-1}$. The isolation criteria of Reda et al. (2004) require isolated galaxies to have no comparable-mass neighbors within 2 B-band magnitudes, 0.67 Mpc in the plane of the sky and 700 km s^{-1} in recession velocity. But we also find that the criterion of radial distance used by these authors is much larger than that of the projected separation. In this article, we will discuss drawbacks of the criteria used to identify isolated galaxies —especially Karachentseva’s (1973) selection algorithm, and some points to be considered in developing a better method. Our paper is organized as follows. In § 2, we describe the data used. Drawbacks of the criteria used to identify isolated galaxies

are discussed in § 3. Our main results and conclusions are summarized in § 4.

2. DATA

York et al. (2000) provided the technical summary of the SDSS. The imaging camera was described by Gunn et al. (1998), while the photometric system and the photometric calibration of the SDSS imaging data were separately outlined by Fukugita et al. (1996), Hogg et al. (2001) and Smith et al. (2002). Pier et al. (2003) described the methods and algorithms involved in the astrometric calibration of the survey, and presented a detailed analysis of the accuracy achieved. Many of the survey properties were discussed in detail in the early data release paper (Stoughton et al. 2002). The main galaxy sample (Strauss et al. 2002) comprises galaxies brighter than $r_p < 17.77$ (r -band apparent Petrosian magnitude). This sample has a median redshift of 0.10 and few galaxies beyond $z = 0.25$, in which most galaxies are within redshift region $0.02 \leq z \leq 0.2$.

The data were downloaded from the Catalog Archive Server of SDSS DR6 (Adelman-McCarthy et al. 2008) by the SDSS SQL Search (with SDSS flag: bestPrimtarget&64 > 0) with high-confidence redshifts ($Zwarning \neq 16$ and $Zstatus \neq 0, 1$ and redshift confidence level: $zconf > 0.95$; <http://www.sdss.org/dr6/>). There are 469,199 main galaxies in the redshift region $0.02 \leq z \leq 0.2$. The main galaxy sample is an apparent-magnitude limited sample, in which fainter galaxies are progressively missed with increasing distance from the observer. In such a sample, selection effects are rather complicated. A simple replacement is to use a volume-limited sample, which has several important advantages: the radial selection function is approximately uniform, thus the only variation in the space density of galaxies with radial distance is due to clustering. But in the volume-limited sample, fainter galaxies are excluded at all distances from the observer; a large fraction of the data is not used. In our work, we used the volume-limited main galaxy sample constructed by Deng et al. (2007b), which contains 112,889 galaxies, extends to $Z_{max} = 0.089$, and is limited to the absolute magnitude region $-22.40 \leq M_r \leq -20.16$. The absolute magnitude M_r is calculated from the r -band apparent Petrosian magnitude, using a polynomial fit formula (Park et al. 2005a) for the K -correction (Blanton et al. 2003) within $0 < z < 0.3$

$$\begin{aligned} K(z) = & 2.3537(z - 0.1)^2 + 1.04423(z - 0.1) \\ & - 2.5 \log(1 + 0.1). \end{aligned}$$

In calculating the distance, we used a cosmological model with a matter density $\Omega_0 = 0.3$, cosmological constant $\Omega_A = 0.7$, Hubble's constant $H_0 = 100 h \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$, where $h = 0.7$.

3. DRAWBACKS OF THE CRITERIA USED TO IDENTIFY ISOLATED GALAXIES

Galaxies in groups or clusters and isolated galaxies are located at both extremes of density. Thus, the criteria used to identify isolated galaxies must ensure that isolated galaxies did not lie in groups or clusters. For group identification, the friends-of-friends (FoF) algorithm developed by Huchra & Geller (1982) is the most frequently applied method. The FoF algorithm starts with any galaxy as the beginning of a trial group. A search for companions around the starting galaxy is carried out with the following criteria:

$$D_{ij} = 2 \sin\left(\frac{\theta_{ij}}{2}\right) D \leq D_L = D_0 R_L,$$

and

$$V_{ij} = |V_i - V_j| \leq V_L = V_0 R_L,$$

where D_{ij} is the projected distance, θ_{ij} the angular separation, $D = \frac{D_i + D_j}{2}$ the mean radial comoving distance, and V_{ij} the line-of-sight velocity difference. All companions and the starting galaxy are added to the group. Then, each of the new group members is in turn used as a center to search for its companions to add to the growing group, continuing until no more sufficiently close new galaxies are found.

The choice of the FoF parameters depends on goals of the authors. In this study, we apply the FoF algorithm with constant linking lengths developed by Berlind et al. (2006)

$$D_{\perp,ij} = (c/H_0)(z_i + z_j) \sin(\theta_{ij}/2) \leq 0.14 \times \bar{n}^{-1/3},$$

$$D_{//,ij} = (c/H_0)|z_i - z_j| \leq 0.75 \times \bar{n}^{-1/3},$$

where \bar{n} is the mean number density of galaxies. A total of 4166 groups with richness $N \geq 4$ (N is the number of member galaxies in each system) are identified. There are 55,412 member galaxies in groups, about 49.1% of total galaxy number in the volume-limited sample. The richest system contains 14,898 galaxies, which is a huge Great Wall of galaxies (Gott et al. 2005; Deng et al. 2006b). Here, we intend to test the fraction of isolated galaxies in groups or clusters.

Karachentseva (1973) used as the main criterion that isolated galaxies do not show companions within 20 diameters in the PSS plates. Using Karachentseva's (1973) main criterion $x_{i,j} \geq 20 \times a_j$, we extract 52,046 isolated galaxies from the volume-limited main galaxy sample, among which 18,402 isolated galaxies, about 35.36% of total number of isolated galaxies, are in groups or clusters. Thus, it is not surprising that Stocke et al. (2004) found that optical luminosity functions of very isolated early-type galaxies in Karachentseva's (1973) Catalog of Very Isolated Galaxies show no statistical

differences when compared to luminosity functions dominated by group and cluster galaxies.

In the SDSS, R_{50} and R_{90} are the radii enclosing 50% and 90% of the Petrosian flux, respectively. If we use the r -band R_{90} ($R_{90,r}$) as the radius of galaxy size, the mean projected galaxy diameter on the sky is ≈ 20.8 kpc for our volume-limited main galaxy sample. In order to ensure that isolated galaxies did not lie in groups or clusters, the criterion of the projected separation for the identification of isolated galaxies should at least be larger than the projected linking length used to identify groups. But we note that Karachentseva's (1973) main criterion $x_{i,j} \geq 20 \times a_j \approx 0.42$ Mpc and Reda et al.'s (2004) isolation criterion (0.67 Mpc) in the plane of the sky are much smaller than the projected linking length used by Berlind et al. (2006): $D_{\perp,ij} = (c/H_0)(z_i + z_j) \sin(\theta_{ij}/2) \leq 0.14 \times \bar{n}^{-1/3} \approx 0.95$ Mpc. They result in finding that a larger proportion of isolated galaxies lie in groups or clusters.

Because the group criteria used by most authors were expressed as a function of the mean number density of galaxies, the isolation criteria used to identify isolated galaxies also should be a function of the mean number density of galaxies, in order to ensure that isolated galaxies did not lie in groups or clusters. In addition, we should use the same isolation criteria in the radial and projected directions to decrease the projection effect. Deng et al. (2006a) used the three-dimensional cluster analysis (Einasto et al. 1984) by which the sample can be separated into isolated galaxies, close double and multiple galaxies, galaxy groups, or clusters. At larger radii, most galaxies of the sample form groups or clusters, and few galaxies are isolated. These isolated galaxies should be a good sample for studies of three-dimensional isolated galaxies. But it is important to realize that we do not have any a priori defined neighborhood radius to identify isolated galaxies. As is well known, galaxy properties are strongly correlated with environment; for example, galaxies in dense environments (i.e., clusters or groups) have predominantly early-type morphologies (e.g., Oemler 1974; Dressler 1980; Whitmore et al. 1993; Deng et al. 2007a), while galaxies in the lowest density regions (isolated galaxies) have a lower proportion of early-type galaxies (e.g., Deng et al. 2006a). In this study, the concentration index $c_i = R_{90}/R_{50}$ is used to separate early-type (E/S0) galaxies from late-type (Sa/b/c, Irr) galaxies (Shimasaku et al. 2001). The galaxy morphology is closely correlated with many other parameters, such as color and concentration index. These parameters can be used as the morphology classification tool (e.g., Shimasaku et al. 2001; Strateva et al. 2001; Abraham et al. 2003; Park & Choi 2005b; Yamauchi et al. 2005; Sorrentino et al. 2006). The concentration index is a simple morphological parameter. Nakamura et al. (2003) showed that $c_i = 2.86$ separates galaxies at S0/a with a completeness of about 0.82 for both late and early types. As shown by Deng et al. (2007a), galaxy morphologies seem to be most sensitive to the environments. Figure 1 shows how the early-type fraction of isolated galaxies changes with

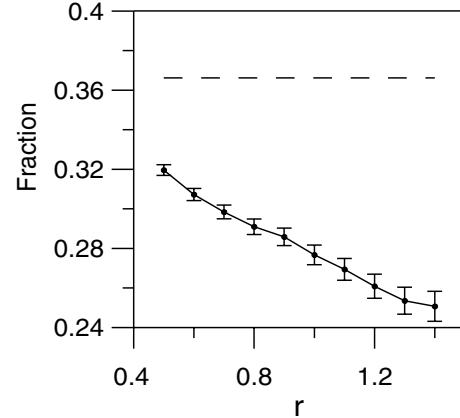


FIG. 1.—Early-type fraction of isolated galaxies as a function of dimensionless radii r . The error bars are 1σ Poissonian errors. The dashed line represents the early-type fraction of the volume-limited main galaxy sample.

growing dimensionless radii $r(r = R/R_0, R_0 = (\frac{3}{4\pi\bar{n}})^{1/3})$ is the radius of the sphere with unit population). The density around isolated galaxies is $n_i \leq 1/(\frac{4\pi}{3}R^3)$. Therefore, the density contrast around isolated galaxies is $(n_i - \bar{n})/\bar{n}$. Figure 2 also shows the density contrast around isolated galaxies as a function of dimensionless radii r . As seen from these two figures, the early-type fraction of isolated galaxies and the density contrast around isolated galaxies drops dramatically with increasing dimensionless radii r . The early-type fraction of isolated galaxies is much smaller than that of the volume-limited sample. This requires us to consider two factors when defining neighborhood radius to identify isolated galaxies: (1) the neighborhood radius is as large as possible, in order to show significant differences when performing the statistical comparisons between isolated galaxies and other families (i.e. clusters or groups); (2) the number of isolated galaxies must be sufficient for statistical analysis. At $r = 1.0$, the density contrast around isolated

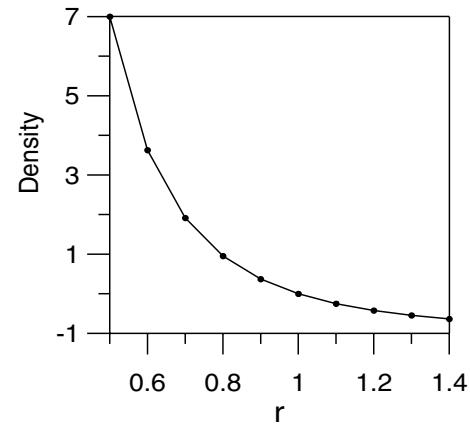


FIG. 2.—Density contrast around isolated galaxies as a function of dimensionless radii r .

galaxies approximates to 0. Because isolated galaxies lie in the most underdense regions, the dimensionless radii r should be at least larger than $r = 1.0$ which corresponds to the neighborhood radius $R = 1.0 \times R_0 \approx 4.23$ Mpc (R_0 for the volume-limited main galaxy sample is 4.23 Mpc). At such a large neighborhood radius, it is not necessary to consider Karachentseva's (1973) additional criterion $\frac{1}{4}a_j \leq a_i \leq 4 \times a_j$, which ensures that any neighboring galaxies have no significant effect on the primary galaxy.

Einasto et al. (1987) showed that the morphology distribution of isolated galaxies does not practically depend on the neighborhood radius used to separate isolated galaxies from groups and cluster, which is not consistent with our conclusion.

In order to investigate the dependence of galaxy luminosity on environment, Deng et al. (2007b) compared the luminosity distribution of member galaxies of groups with that of isolated galaxies identified at dimensionless radius $r = 1.4$. Since the density contrast $(n_i - \bar{n})/\bar{n} < -0.64$ around these isolated galaxies is lower than the density contrast $(n_i - \bar{n})/\bar{n} < -0.6$ around void galaxies identified by Rojas et al. (2004), Deng et al. (2007b) claimed that isolated galaxies identified at $r = 1.4$ are located in particularly low-density environments. Here, we perform comparative studies of distributions of luminosity and colors between two samples of isolated galaxies identified at dimensionless radii $r = 1.0$ and $r = 1.4$ respectively, to investigate the dependence of properties of isolated galaxies on the degree of isolation.

We divide the whole luminosity region ($-22.40 \leq M_r \leq -20.16$) into 10 bins of width 0.224. The (1σ) error bars are Poissonian errors. Figures 3 and 4 show the luminosity and color distributions of isolated galaxies identified at $r = 1.0$ (blue line) and $r = 1.4$ (red line), respectively. We do not

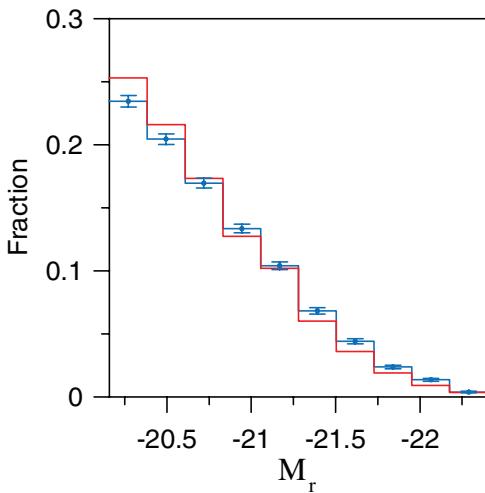


FIG. 3.—Luminosity distributions of isolated galaxies identified at $r = 1.0$ (blue line) and $r = 1.4$ (red line), respectively. The error bars are 1σ Poissonian errors for isolated galaxies identified at $r = 1.0$.

observe large statistical differences between two isolated galaxy samples; the level of significance is smaller than 2σ in most bins, which shows that the luminosity and color distributions of isolated galaxies depend weakly on the degree of isolation. It has been known for a long time that morphologies, luminosity, and colors of galaxies correlate with environment, but for different galaxy properties, the sensitivity to environment may be different. Deng et al. (2007c) measured for each galaxy the local density within the distance to the fifth and the tenth nearest galaxy, and found that galaxy morphologies strongly depend on local environment, but that the mean luminosity, size, and colors of galaxies are insensitive to environment. Deng et al. (2007a) also reached similar conclusions. Thus, if we intend to define a neighborhood radius to identify isolated galaxies by the environmental dependence of galaxy properties, galaxy morphologies are a better choice.

For identification of groups, there is not a widely accepted criterion. For different galaxy samples, many authors often developed different algorithms and criteria. Berlind et al. (2006) suggested that identifying the correct linking lengths to identify groups depends on the scientific objectives of the work. Here, we also preferentially believe that the choice of neighborhood radius used to identify isolated galaxies depends on our specific goals. If it is clear that the number of isolated galaxies is sufficient for statistical analysis, we always hope that the neighborhood radius is as large as possible, in order to show more significant statistical differences of galaxy properties between isolated galaxies and other families.

4. SUMMARY

Using the volume-limited main galaxy sample of SDSS DR6, we explore drawbacks of the selection criteria of isolated galaxies developed by Karachentseva (1973). By the algorithm of Berlind et al. (2006), we construct a group sample containing 55,412 member galaxies, to test the fraction of isolated galaxies in groups or clusters. It is found that about 35.36% isolated galaxies identified by Karachentseva's (1973) main criterion $x_{i,j} \geq 20 \times a_j$ lie in groups or clusters, due to Karachentseva's (1973) main criterion in the plane of the sky being much smaller than the projected linking length used by Berlind et al. (2006). Use of this criterion may result in an absence of significant statistical differences when comparing properties of group and cluster galaxies with those of isolated galaxies identified by such algorithms. The group criteria used by most authors have often been expressed as a function of the mean number density of galaxies. This suggests that we should express the isolation criteria using parameters that are a function of the mean number density of galaxies; for example, the dimensionless radii r or the density contrast $(n_i - \bar{n})/\bar{n}$. In addition, we notice that the morphology distribution of isolated galaxies depends strongly on the dimensionless radii, but the luminosity and color distributions of isolated galaxies depend weakly on the degree of isolation. Such results suggest that galaxy morphologies are a better choice to

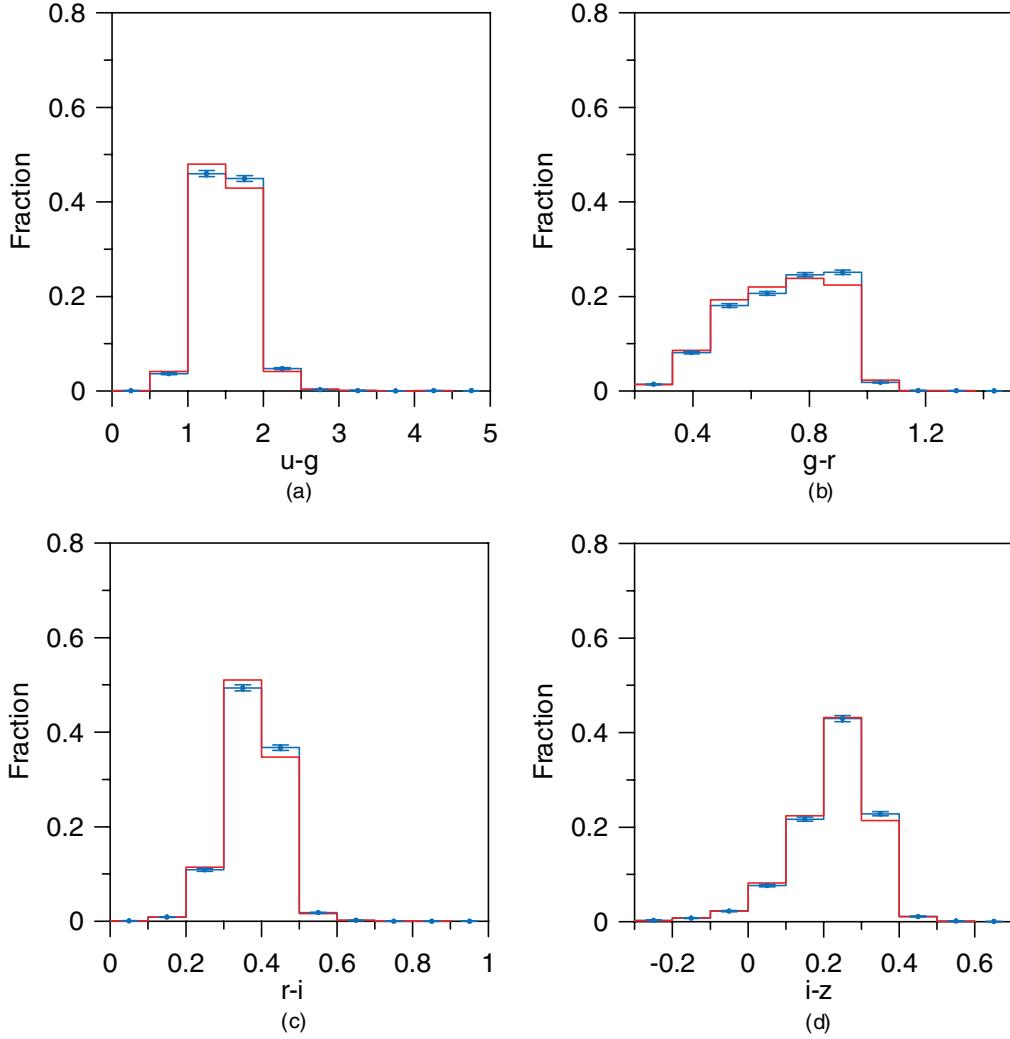


FIG. 4.—Color distributions of isolated galaxies identified at $r = 1.0$ (blue line) and $r = 1.4$ (red line), respectively. The error bars are 1σ Poissonian errors for isolated galaxies identified at $r = 1.0$. (a) $u-g$ color, (b) $g-r$ color, (c) $r-i$ color, (d) $i-z$ color.

define a neighborhood radius for identification of isolated galaxies based on the environmental dependence of galaxy properties.

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